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Evaluation of Parameters used in Progressive Damage Models

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Evaluation of Parameters used in Progressive Damage Models

- Motivation and Key Issues
  - The matrix-compression material-model used in Abaqus for carbon fiber laminates is computationally efficient but is physically unrealistic and does not correspond to actual material behavior.
- Objective
  - Determine the conditions under which the use of this unrealistic material model causes significant errors in predictions of carbon fiber laminate response to load and load-carrying ability.
- Approach
  - Conduct experimentation to determine a physically-correct matrix-compression material model
  - Implement this material model in Abaqus and compare its predictions with those of the currently-used material model

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Personnel

- Principal Investigators & Researchers
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- Industry Participation
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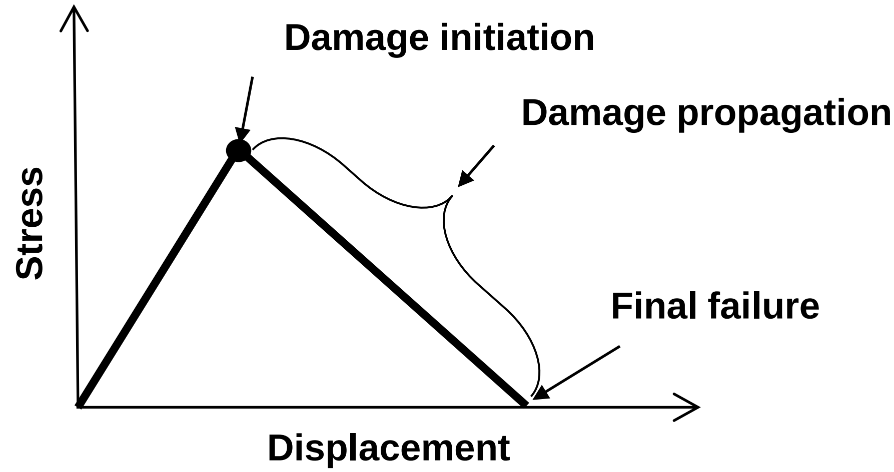
Today's Topics

- Background (the reason for our work)
- Our Prior work (a useful review of what we have done)
- Today's new content
  - Specimen Manufacturing
    - Commercial Material
    - Proprietary Material
  - Specimen Use
    - LEFM determination
    - Propagation Testing Procedures
    - Energy Release rate
- Future plans

Background



- Currently the same simple triangular material model is used for both matrix tension and compression in Abaqus (often with the same parameters)
- The model consists of
  - A linear elastic region culminating in the point of maximum load carrying ability at damage initiation
  - A linear plastic region beginning at damage initiation, including all damage propagation, and ending with no load carrying ability
- This model is reasonable for **matrix tension** in which accumulation of damage during propagation causes material separation and a corresponding reduction in load-carrying ability
- This model does not seem reasonable for **matrix compression** in which damage propagation causes an accumulation of debris which retains some load-carrying ability
- Our first task was to develop a suitable test specimen to observe matrix compression damage initiation and propagation.

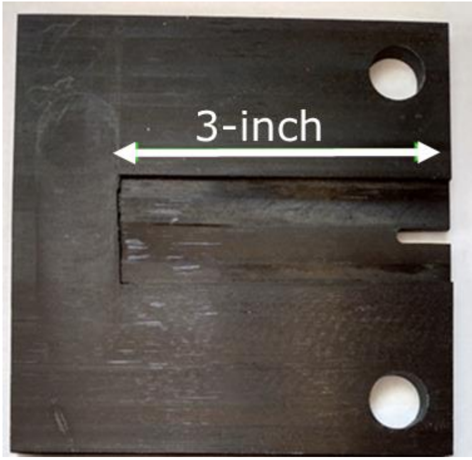
Our Prior Work

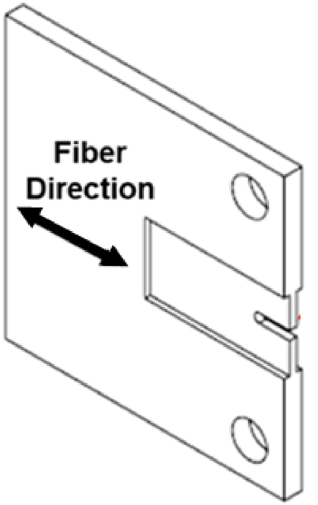
A Compact Compression specimen called the ***Stepped Specimen*** was developed to isolate matrix compression damage initiation and propagation. Geometry consists of:

- 15-plies near the notch tip (thin region), 35 plies elsewhere (thick region).
- 3-inch thin region for crack propagation.

Specimen development has been described in prior presentations….

It took some work to get here!





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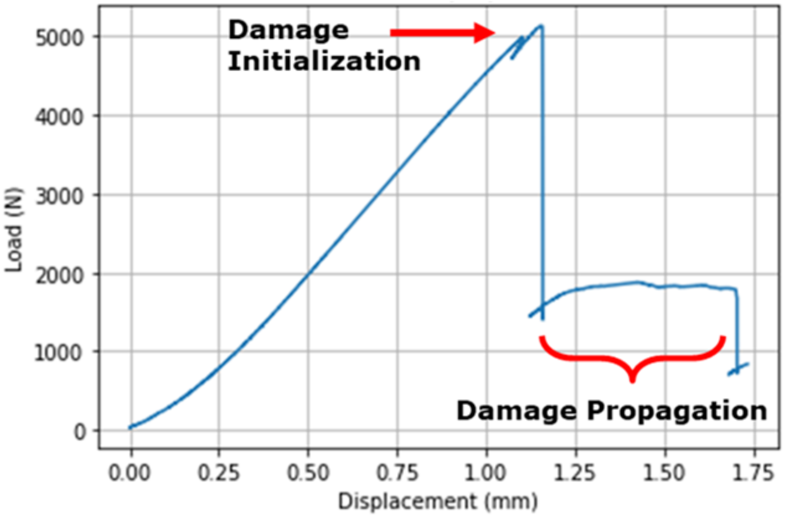
Our Prior Work

Preliminary testing showed that:

- **The specimen works well**, creating significant compression damage prior to tensile failure.
- A simple triangular material model is not physically correct for matrix compression
- The matrix compression toughness value is significantly different from the matrix tension value.

- Additional testing requires a relatively large number of specimens and improved manufacturing methods



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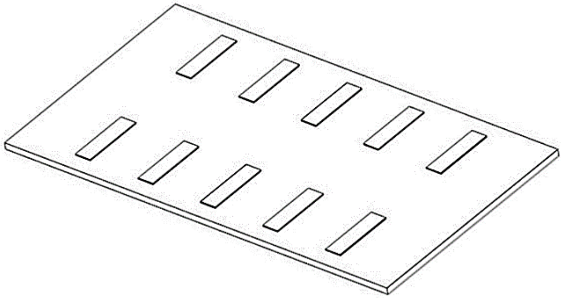
Today's New Content: Specimen Manufacturing

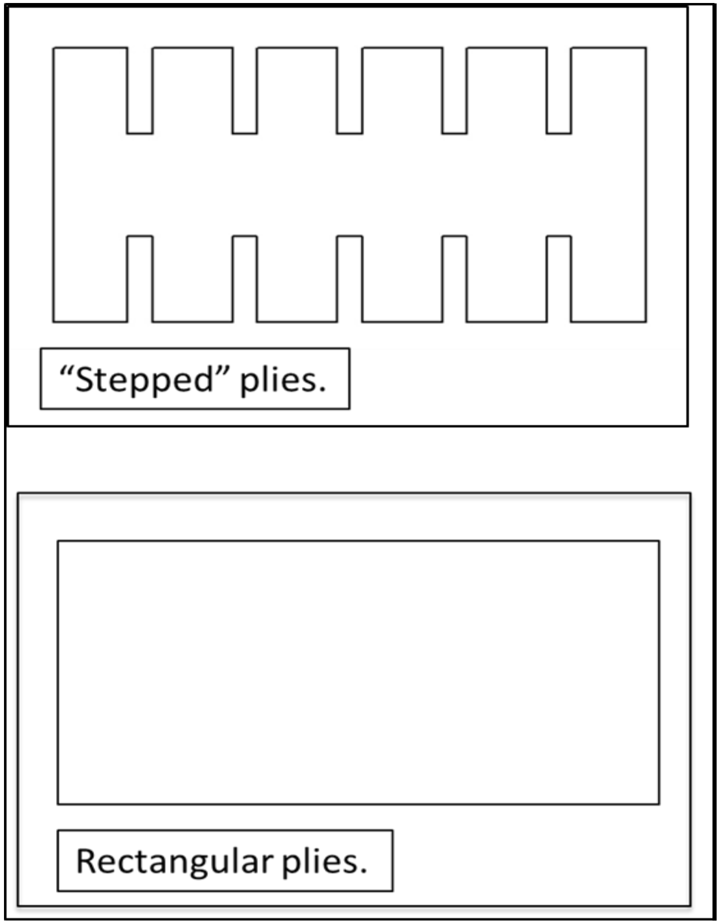


A layup plate was designed for mass manufacturing of Stepped Specimens.

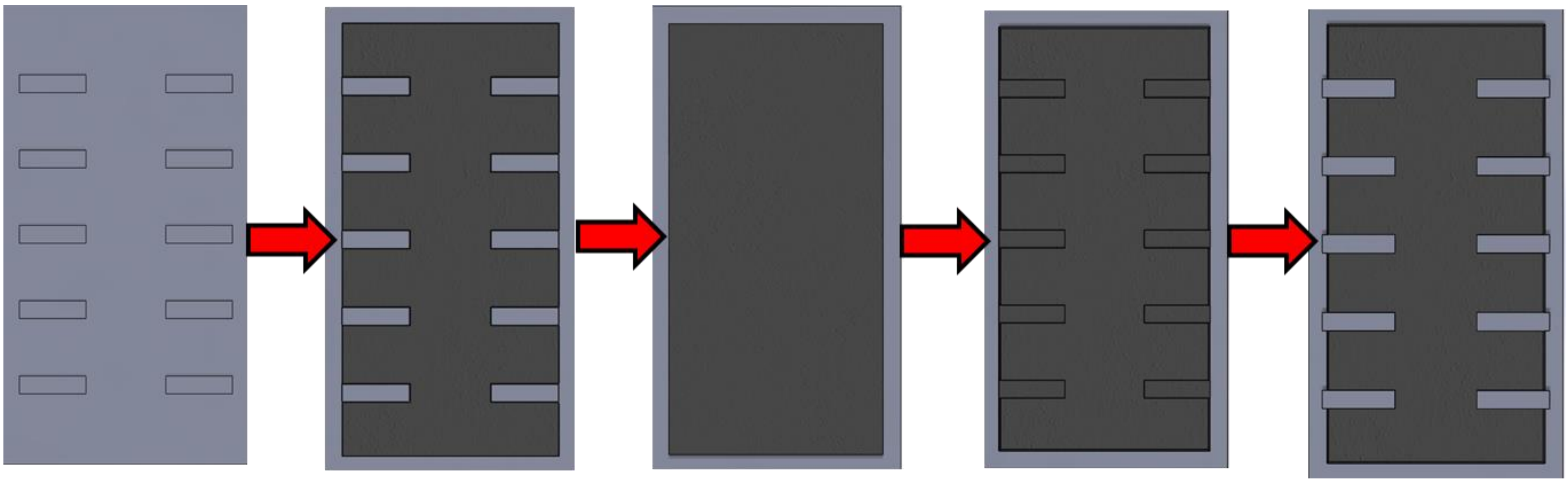
- Plate consisted of 10 steps machined into the plate and made a total of 10 specimens per a layup. This plate was called the ***Machined Step Plate***.

- Layup Procedure consisted of 20 stepped plies and 15 rectangular plies. Layup procedure is detailed in the following text.
  - 10 stepped plies are laid on top of the machined step plate.
  - 15 rectangular plies are then laid on top of the 10 stepped plies.
  - 10 steel shims are then placed in line with the machined steps on top of the rectangular plies. After the shims are placed, 10 stepped plies are laid in-between the steel shims to complete the layup procedure.

Images of this process are shown on the following slide.



Today's New Content: Specimen Manufacturing

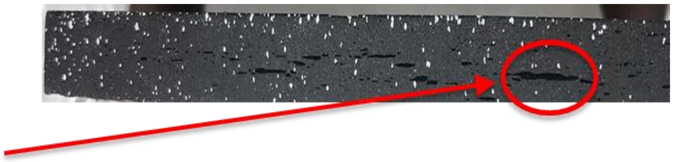


Layup Procedure for the Compact Compression Specimen

Today's New Content: Specimen Manufacturing

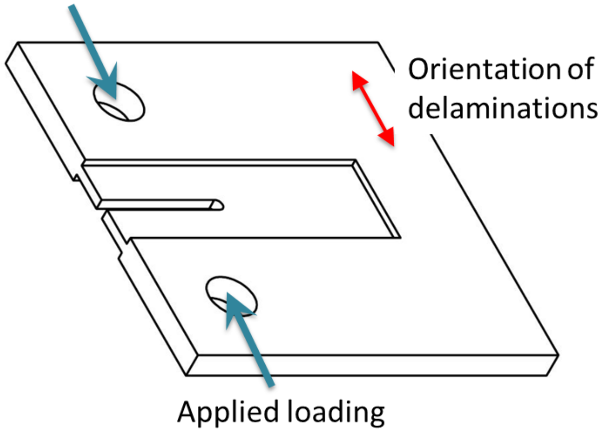
Manufacturing defects with the commercial material

- Manufacturing problems occurred with the commercial material specimens. Delaminations existed between the plies in the 'thick' region.



Cause of Problem

- Subsequent testing has confirmed that the delaminations were caused by high moisture content, low applied pressure, and a low debulking time.



Solution

- Adjusted processing parameters resulted in minimal delaminations.

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Today's New Content: Specimen Manufacturing

Additional Manufacturing problem:

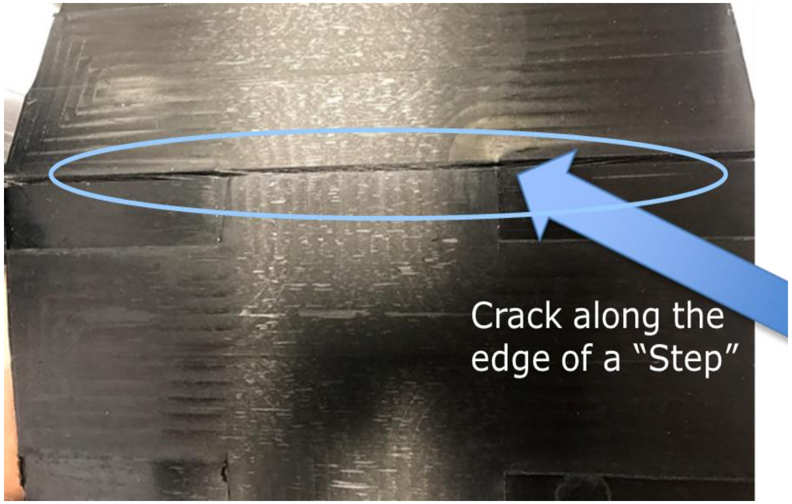
- Additional manufacturing problem occurred with the Machined Step Plate (with commercial material).
- The cracks along the edges of the thin region as shown.

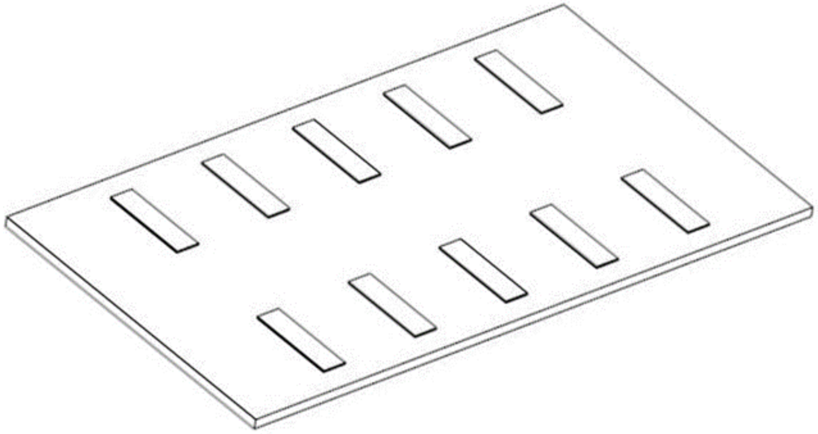
Cause:

- Cracks appeared during separation of cured laminate from the aluminum plate (large amount of bending).

Solution:

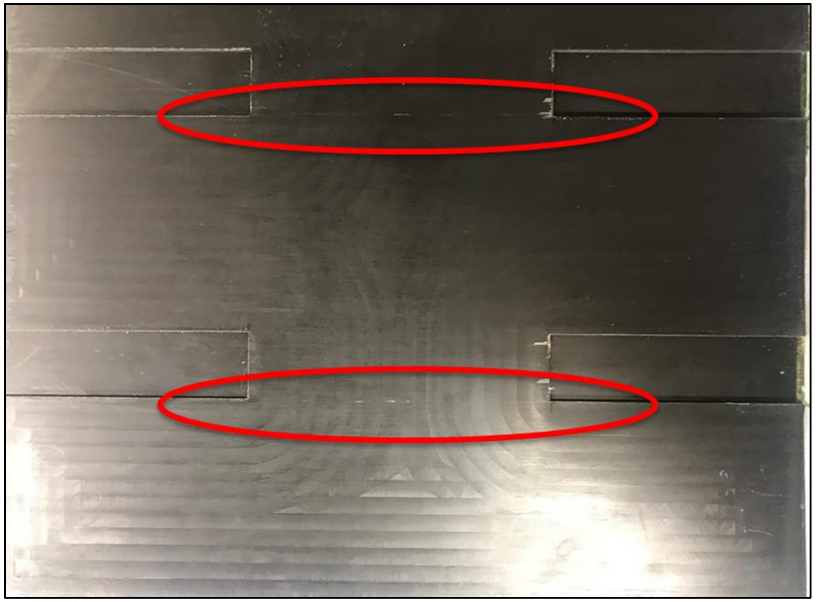
- Layup method was changed by altering ply geometry, switching fiber release agent and the separation tool.





Today's New Content: Specimen Manufacturing

- The revised manufacturing methods prevented the damage from occurring in commercial material.



Manufacturing problem with Proprietary Material

- However Proprietary material still had cracking. Also surface delaminations occurred.

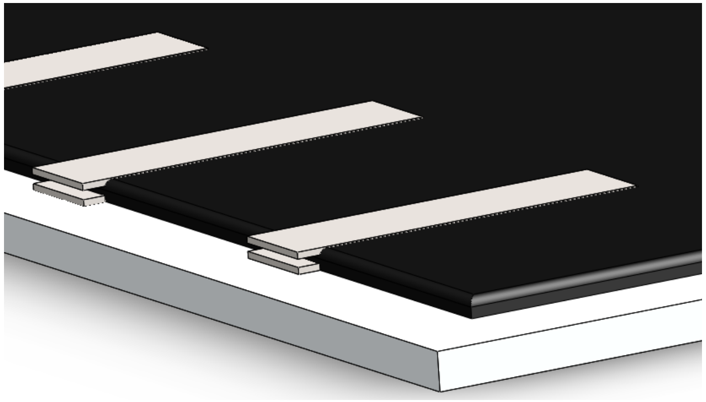
Cause:

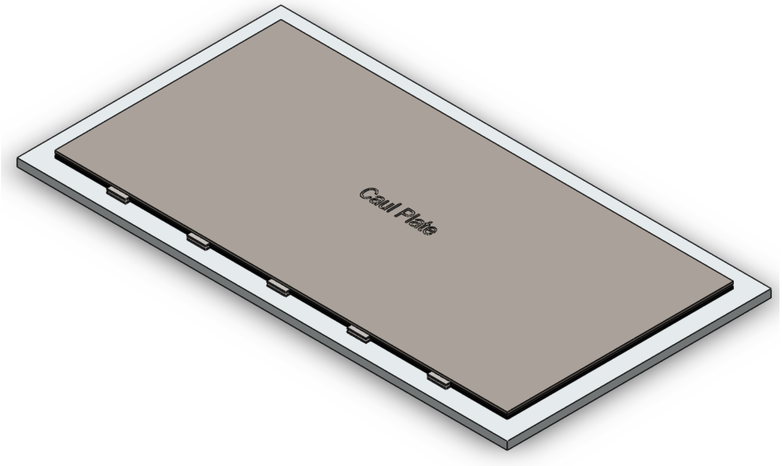
- Industry partners concluded that the material contracts during the cure cycle. The rigid steps in the aluminum plate are damaging the carbon fiber during cure.

Today's New Content: Specimen Manufacturing

Solution:

- To reduce cracks from occurring to the material a the new layup method was used that introduced an additional degree of freedom.
- By using shims that were not fixed to the plate, they were free to move with the carbon fiber as it contracted.
- 10 shims for the bottom thin region, and 10 shims on the top of thin region.
- Caul plate was used to reduce delaminations.
- Result: No cracking was induced, and Proprietary-material specimens made with this method had a **~90% success rate** in matrix compression damage initiation and propagation.





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Today's New Content: LEFM Determination

- A primary use of the specimens is to determine the correct matrix compression energy release rate

- Continuum damage mechanics models in FEA software use strain energy release rates to degrade the stiffness of a material. With composites, there are four: Fiber Tension, Fiber Compression, Matrix Tension, and Matrix Compression.

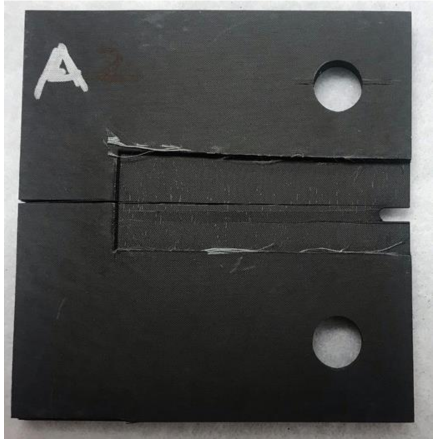
- Matrix Compression has not been investigated thoroughly. An effective method to measure it's energy release rate has not been identified. It is often simply assumed to be equal to the Matrix Tension value or approximated from Mode II loading.

- In order to better understand matrix compression, an investigation was conducted to determine if it followed LEFM (**which had not previously been shown**)

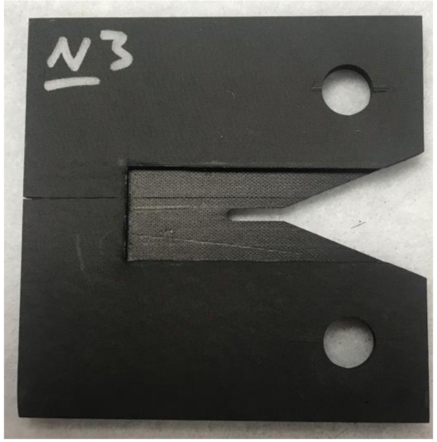
Today's New Content: LEFM Determination

- In linear elastic fracture mechanics, for a specimen with a notch, the failure load is directly related to the notch length. On a log-log plot of failure load vs. notch length, the curve will be linear and have a slope of –(1/2).

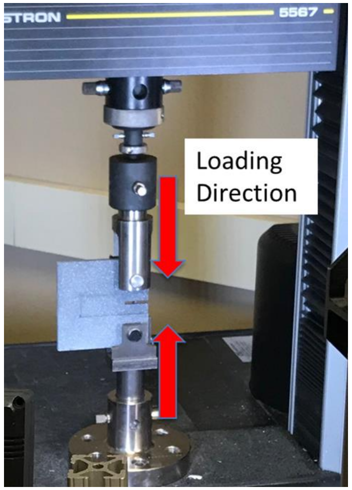
- Varying the notch length of multiple specimens (1/4" – 1 7/8"), and measuring the peak (failure) load, such a plot can be generated, and the trend will reveal LEFM behavior if occurring.



¼" Specimen



1 7/8" Specimen

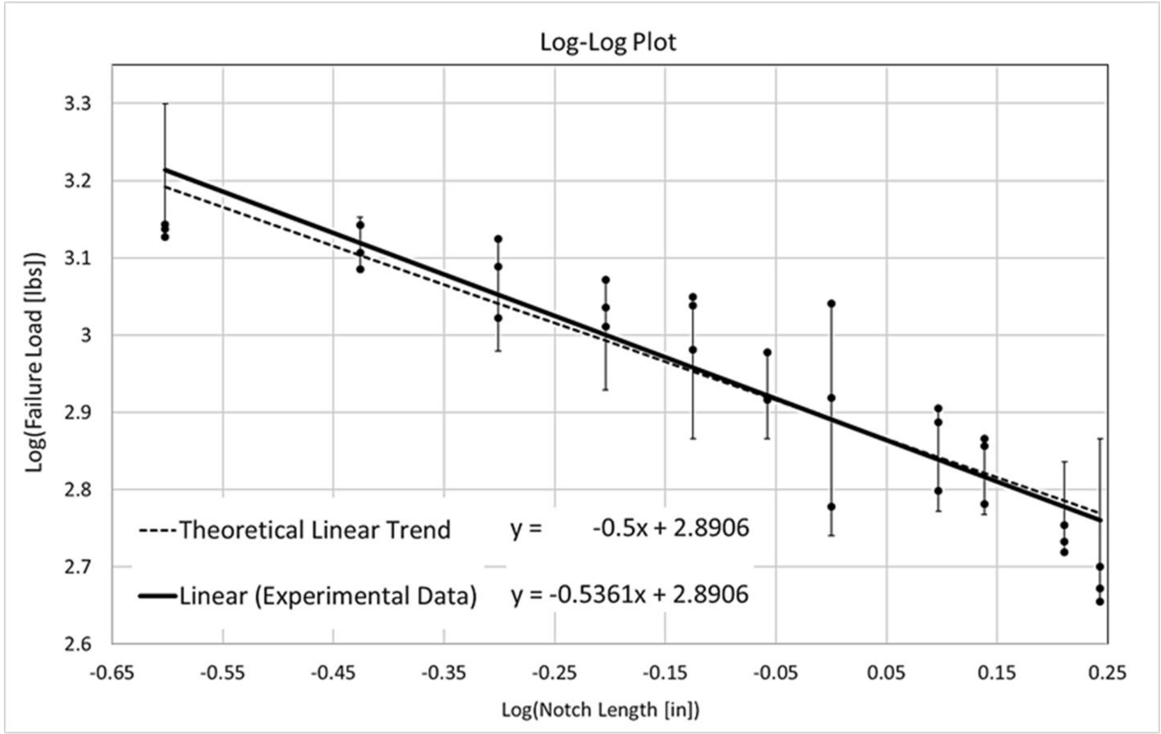


Specimen in loading fixture

- **¼" – 1 7/8" (at 1/8" increments)**
- **3 Specimens per notch length.**
- **1 mm/min compression test**

Today's New Content: LEFM Determination

- Experiments were conducted using commercially-available material.
- The specimens exhibited a decrease in peak load as the notch length was increased.
- The log-log plot of the data on the right follows a linear trend with an R^2 value of 0.83, and a slope of (-0.54 ± 0.22).
- The matrix in compression has been experimentally shown to follow the laws of LEFM.



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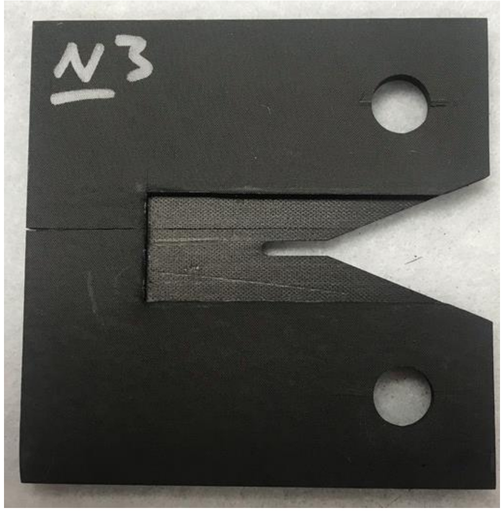
Today's New Content: Propagation Testing Procedures

- The matrix compression specimen developed in the study necessarily has finite notch radius (to allow clearance for subsequent compression).



- Simply studying crack propagation from this notch will introduce effects dependent on the tip radius dimension

- When conducting tensile crack propagation studies similar effects are dealt with by introducing a sharp crack tip in the specimen.

- We next explore an effective means of introducing a suitable sharp crack tip in our matrix compression specimen

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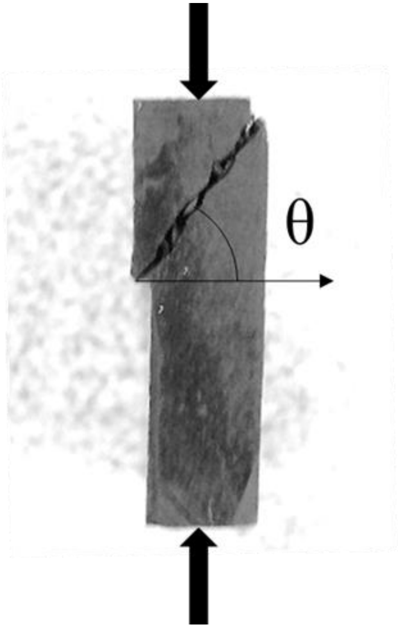
Today's New Content: Propagation Testing Procedures

- To focus on this region of interest, compact tension specimen literature was explored.
- It was found that most compact tension specimens have a sharp starter crack placed into the specimen with either a diamond wire, razor saw, or a razor blade to get fracture toughness values for tension. With this in mind it was decided to introduce starter cracks into the specimens to see if these will help the focus on matrix compression propagation.

- Matrix compression tests were conducted at displacement rate of 1 mm/min using specimens with either
  - a 0° fracture-angle starter crack
  - a 45° fracture-angle starter crack
  - no starter crack (baseline). Baseline specimens were tested to have a direct comparison.
- All starter cracks were made with a diamond wire.



Fracture surface with fracture angle shown as θ.

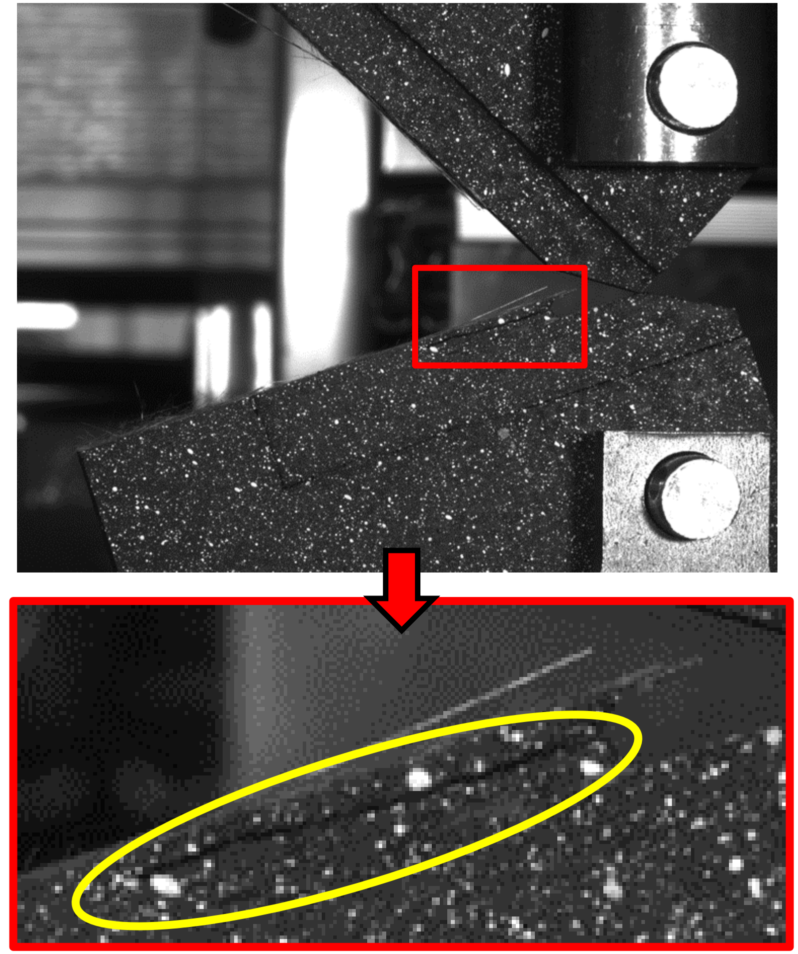
Today's New Content: Propagation Testing Procedures

- The 0° fracture angle cracks failed in tension, similar to specimens with a long notch length (1.875"), which were too long for the specimen geometry.

- 45° fracture angle cracked specimens had compression damage occur before tensile failure. But this compressive damage had a large crack jump (Nonstable propagation) similar to the initiation from a blunt crack tip (notch tip) .

- Baseline specimens were all successful in matrix compression damage initiation and propagation.

- Result: Starter cracks were unable to aid matrix compression propagation



0° Starter Crack Specimen Tensile Failure. (Starter Crack is in red square)

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Today's New Content: Propagation Testing Procedures

- The reason starter cracks do not work with matrix compression is due to compressive crack having a complex fracture surface. A compressive fracture surface creates a "V" or "W" crack shape unlike tension damage which creates a straight (0°) fracture surface through the thickness of the specimen (Crack Surfaces shown below).

A

B

C

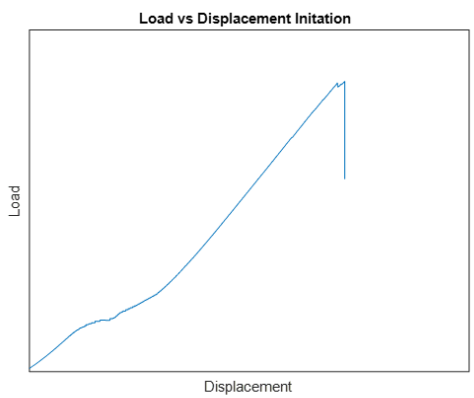
A: Fracture surface of the starter crack (0°) with a compression crack surface forming afterwards ("W") .

B: "V" fracture surface that occurs with a compression crack.

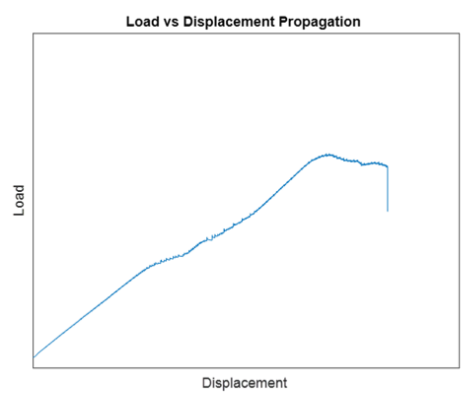
C: "W" fracture surface that occurs with a compression crack.

Today's New Content: Propagation Testing Procedures

- Since starter cracks cannot be introduced by machining-induced methods, another procedure was explored. This new method consisted of compressing the specimen until a natural crack occurs. Then, the instant the crack is formed, the specimen is fully unloaded to prevent further crack propagation. Once unloaded, the specimen is reloaded for the crack propagation study until tensile failure occurs on the back edge of the specimen.
- **This method worked**, as all specimens tested had a matrix compression damage initiation occur (figure on the left). Then after being unloaded and then reloaded, specimens had damage propagation occur in which propagation data was collected (figure on the right).



Typical load displacement curve for matrix compression initiation with proprietary material.



Typical load displacement curve for matrix compression propagation with proprietary material.

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Today's New Content: Propagation Testing Procedures

- Although this method works for our propagation focus, there are still a few concerns with this method:
  - Fully unloading the specimen results in specimen not loaded in the same orientation.
  - Specimens have to be preloaded twice (1 for initiation, 1 for propagation).

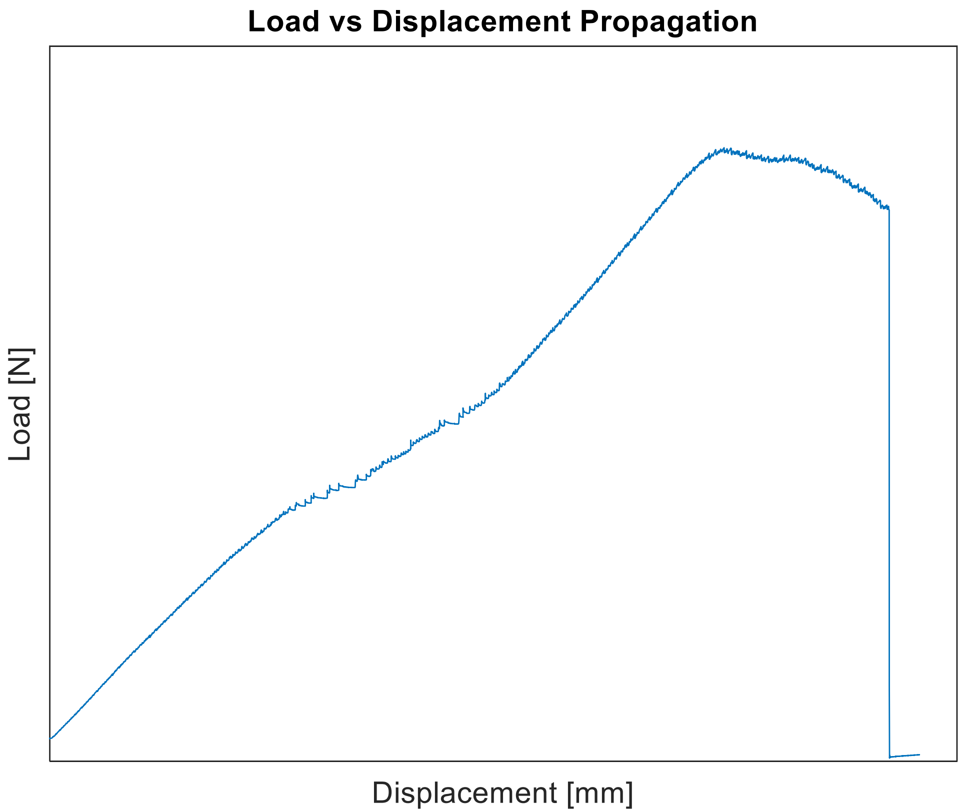
- To minimize these concerns, it was suggested that instead of unloading the specimen fully we unload the specimen back to the original pre-load. This would allow the specimen to be unloaded while also not allowing the specimen to change orientation during the two tests.

Today's New Content: Propagation Testing Procedures

- Modified test procedures allowed us to only have to preload the specimen once while still having an isolated crack propagation test.

- This resulted in successful matrix compression propagation similar to the previous method without preload and specimen orientation concerns.

- As this method minimizes most concerns, all further propagation tests will be conducted following this procedure.



Load-Displacement Curve for propagation for proprietary material with this testing method.

Today's New Content: Energy Release Rate

- With testing procedures in place our focus changed to calculating the strain energy release rate due to matrix compression. Multiple methods were explored as there was little literature on the compression energy release rate.
- Further research in energy release rate methods used for tension showed ASTM E399, Area method, Compliance Calibration (CC), Modified Compliance Calibration Method (MCC), and J- Integral were used.
- Due to the nature of compression damage and orthotropic materials certain analysis methods were ruled out. These consisted of ASTM E399 as it is strictly for isotropic materials and the MCC method as it relied on machining starter cracks. This reduced the methods that could be explored.
- Of the methods left the Compliance Calibration method, Area method, J-integral method were explored further.

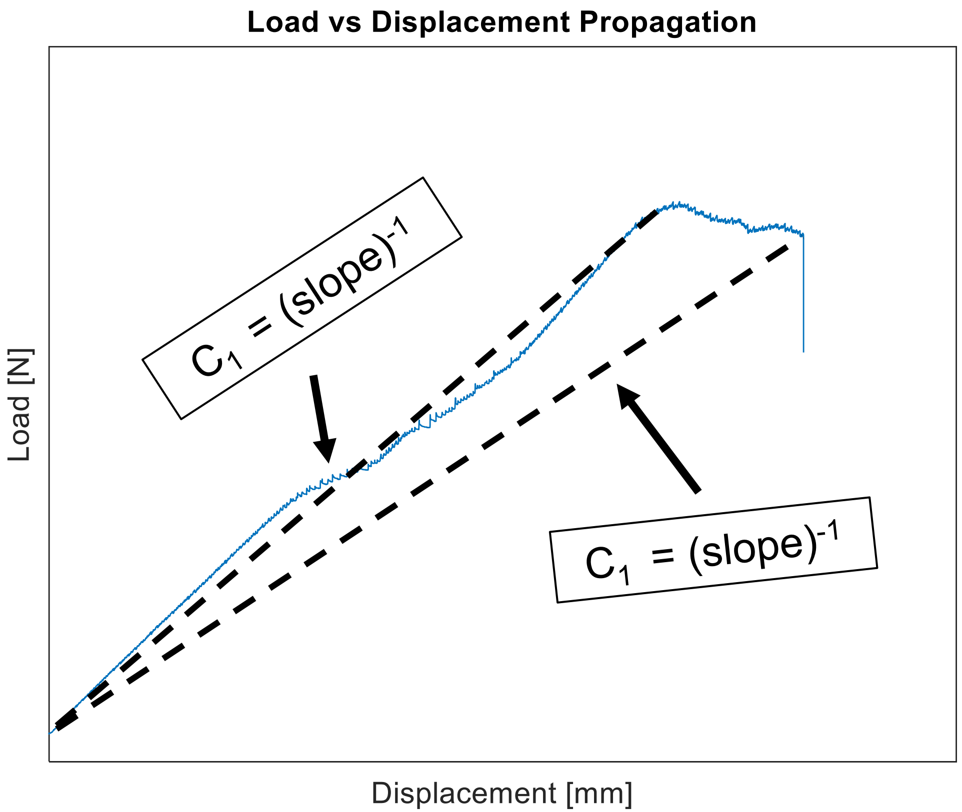
Today's New Content: Energy Release Rate

Compliance Calibration Method:

- This method was used to calculate strain energy by taking the inverse slope of the load displacement data right after crack propagation and before tensile failure.

$$G_c = \frac{P_c^{\,2}}{2B}\frac{dC}{da}$$

- P = Peak Load
- B = Fracture Surface Width
- $dC = C_1 - C_2$
- da =crack extension (measured optically)

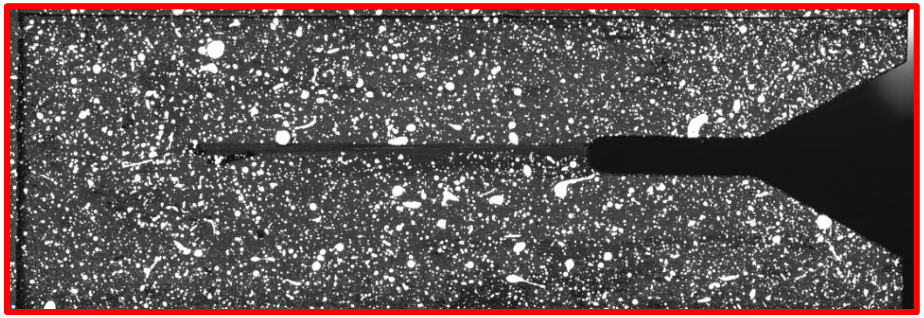


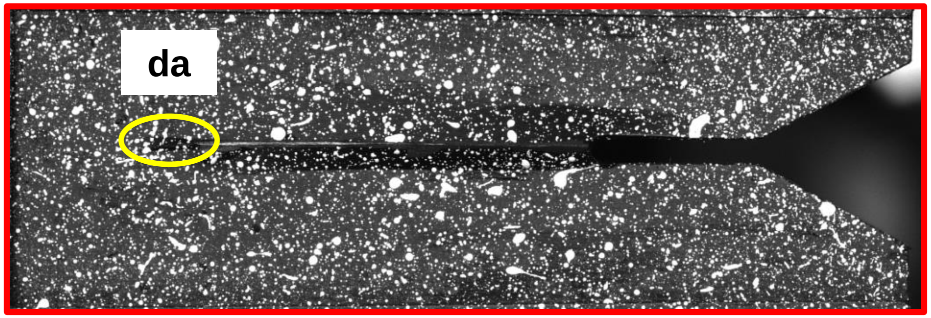
Crack Initiation Energy Release Rate

- The crack extension, da, was determined optically. The cameras recording the specimen during the test, captured the initial crack formed. This crack tip was in the vicinity of a particular speckle pattern. After the test was complete, this particular pattern was found on the specimen, and measured using image software.

- This is done by measuring a known length to get the pixels per length measurement, then measuring the crack pixel length to get the correct crack extension length.

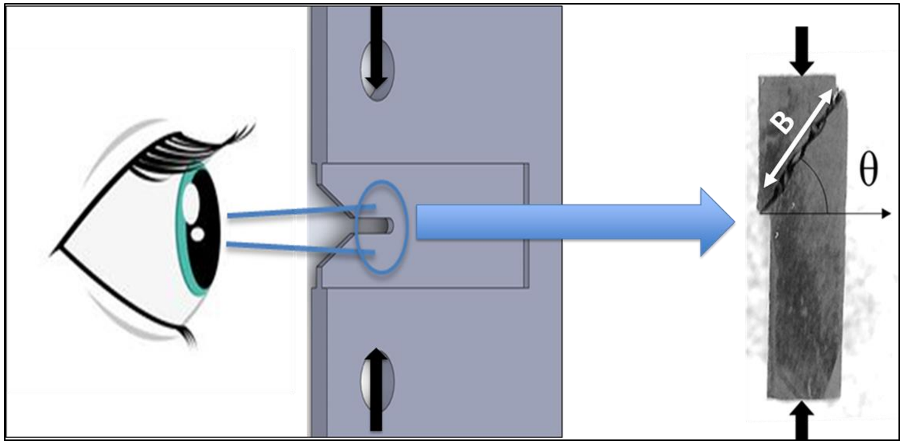
- This measuring method is also used to measure the fracture surface width (B).





Today's New Content: Energy Release Rate

- As with crack length, the fracture surface were measured following the same method as previously stated.
- The reason for this is because the crack occurred at angles such as the "V" or "W" formations shown. So the specimen thickness, alone, could not be used as the entire crack surface width needed to be measured.
- For this reason the crack surfaces were measured using the same software methods.



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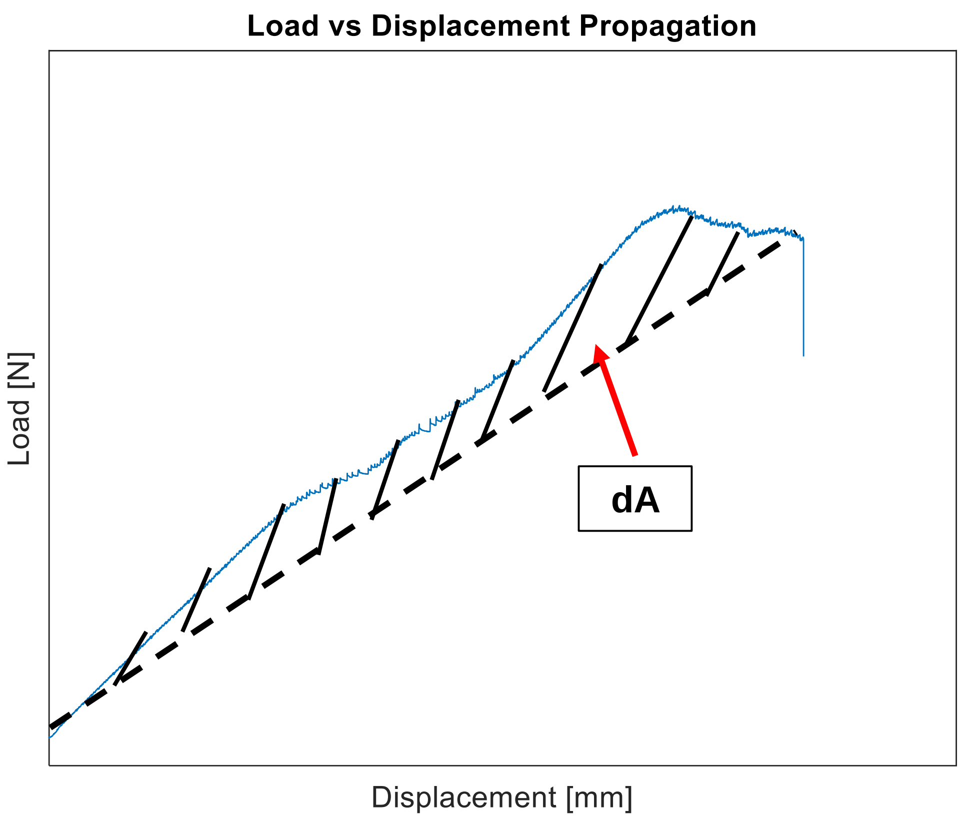
Today's New Content: Energy Release Rate

Area Method:

- To have a direct comparison to the CC method the area method was used. This method is very similar to the CC method but instead of using the inverse of the slope it uses the area under the load displacement data (Energy released). To get the energy released due to compression a sloped line must be calculated from the last data point before tensile failure. The equation is as follows:

$$G_c = \frac{dA}{B * da}$$

- dA= Area under data curve (blue curve) – Area under last data point line (black line)
- B = Fracture Surface Width (measured optically see slide 26)
- da =crack extension (measured optically see slide 26)



Today's New Content: Energy Release Rate

- Using the crack measurement method stated, the compliance calibration method and area method were able to be used.

- **Preliminary results** with these methods (in the following table) show that the currently assumed strain energy release rate value used for matrix compression is not correct as the calculated value is ~7 to 8 times bigger. This shows that the currently assumed value is incorrect.

- Between the two methods there was about a 12% difference in the calculated energy release rate. With this in mind more specimens need to be tested to verify these methods.

Method Used	$\frac{G_{MC\ Calculated}}{G_{MC\ Assumed}}$
CC	7.82
Area	6.90

Conclusions

- We have developed
  - An effective matrix-compression test specimen
  - Corresponding manufacturing procedures
  - Corresponding test procedures
  - Corresponding data analysis procedures

- Work is proceeding on
  - Manufacturing sufficient numbers of specimens for material property testing of both commercial and proprietary materials
  - Training students on the use of Abaqus

- We are on schedule